Design and Perception Testing of a Novel 3-D Autostereoscopic Holographic Display System

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ABSTRACT

U.S. Army Tank-Automotive Command (TACOM) researchers are in the early stages of developing an autostereoscopic, 3-D holographic visual display system. The present system uses holographic optics, low and high-resolution projectors, and computer workstation graphics to achieve real-time, 3-D user-interactivity. This system is being used to conduct 3-D visual perception studies for the purpose of understanding the effects of 3-D in military target visual detection and as an alternative technique to CAD model visualization. The authors describe the present system configuration, operation, some of the technical limitations encountered during the system development, and the results of a human perception test that compared subject response times, hit rates and miss rates of visual detection when subjects used conventional 2-D methods versus the 3-D holographic image produced by the holographic display system. The results of this study revealed that 3D HOE system increased the perception of accuracy of moving vehicles. This research has provided some insights into which technology will be the best for presenting 3-D simulated objects to subjects or designers in the laboratory.

KEY WORDS: holography, optics, stereoscopic, three-dimensional displays, visual perception

1. INTRODUCTION

Stereo vision, which enables depth perception, is an important visual ability of humans, which evolved from our need to survive in complex environments. Most humans have good depth perception. Current technological developments have created the means to simulate with various devices, human 3D perception. However, there is still the debate of whether 3D technology is necessary for certain tasks and applications. For this reason alone, a tremendous amount of fundamental research is being accomplished in the areas of 3D visualization and supporting technologies, for the purpose of investigating new approaches to and applications of 3D displays. U.S. Army Tank-Automotive Command (TACOM) researchers are in the early stages of developing an autostereoscopic, 3D holographic visual display system. The current holographic system is being used to conduct 3D visual perception studies for the purpose of understanding the effects of 3D in military target visual detection and as an alternative technique to CAD model visualization. Within the context of embedded simulation, the authors are working on determining how important 3D is to replicating and presenting the reality of the tactical field situation to subjects in the laboratory environment for testing the detectability of military ground vehicles with different surface treatments. This work supports a larger in-house research effort on novel 3D display technologies. A long-term objective of this research is to develop alternative 3-D visual display devices that can revolutionize current display standards. These new systems could be transitioned into: 1.) new crewstation interface designs providing soldiers with 3-D information to enhance their situational awareness and decision making ability, 2.) robotic manipulation providing improved telepresence using 3-D displays, and 3.)simulation-based acquisition providing exploratory and advanced development programs with the true 3-D virtual replicas to reduce cost, time, and risk.

The purpose of the visual perception test conducted in the U. S. Army TARDEC/NAC Visual Perception Laboratory (VPL) was to evaluate, through empirical testing and data analysis, how 3D visual display systems increase detection rates and decrease false alarms in target detection tasks involving moving cars. The experiment involved presenting real road video of cars and trucks approaching a driveway with their turn signals on. The video was shown to observers in conventional 2D and in 3-D holographic prototype system. The observers were tasked with indicating when they thought they saw a vehicle with its turn signal on. Subject response times, hit rates and miss rates were computed from their responses.

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2. REVIEW OF HOLOGRAPHY

The phase of the light as it travels from point P to point Q is given by: $\phi_p = \frac{2\cdot\pi}{\lambda}\cdot\overline{PQ}$. A constant phase is added (which we will ignore) between two points that are within the coherence length of the laser. By the superposition principle, a hologram is a collection of points. For simplicity, then, we will examine just one point of the object in two dimensions. We also add the reference beam in.

The field emerging from a point is given by the wave equation:

$$u = \cos(k\cdot(x - c\cdot t))$$

where k is a constant conversion factor from distance to radians, and c is the velocity of the wave (the velocity of light),

$$u = \cos\left[\frac{2\cdot\pi}{\lambda}\cdot(x - c\cdot t)\right]$$

$$u = \cos\left(\frac{2\cdot\pi}{\lambda}\cdot x - 2\cdot\pi\cdot f\cdot t\right)$$

$$u = \cos(k\cdot x - \omega\cdot t)$$

$$u = \mathrm{Re}\left(e^{i(k\cdot x - \omega\cdot t)}\right)$$

$$u = \mathrm{Re}\left(e^{i\cdot k\cdot x}\cdot e^{-i\cdot\omega\cdot t}\right)$$

In phasor analysis, the Re( ) is understood, and the $e^{-i\cdot\omega\cdot t}$ term is dropped.

$$u = e^{i\cdot\frac{2\cdot\pi}{\lambda}\cdot x}$$

The field converging to a point is given by reversing time:

$$\overline{u} = \cos(k\cdot(x + c\cdot t))$$

But remember that $\cos(x) = \cos(-x)$

So:

$$\overline{u} = \cos(-k\cdot x - c\cdot t)$$

Following the same arguments as above:

$$\overline{u} = e^{-i\cdot\frac{2\cdot\pi}{\lambda}\cdot x}.$$

The field emerging from point P is given by:

$$u_p = e^{i\cdot\frac{2\cdot\pi}{\lambda}\cdot r_p}$$

where

$$r_p = \left[z_p^{\,2} + \left(x - x_p\right)^2\right]^{\frac{1}{2}}$$

Similarly for the reference beam:

$$u_o = e^{i \cdot \frac{2 \cdot \pi}{\lambda} \cdot r_o}$$

where

$$r_o = \left[z_o^{\ 2} + \left(x - x_o\right)^2 \right]^{\frac{1}{2}}$$

The film of the hologram is linear in intensity, not field, so we find the intensity in the hologram plane (the x-y plane).

$$I = \left(\left| u_o + u_p \right| \right)^2$$

$$I = \left(u_o + u_p\right) \cdot \overline{\left(u_o + u_p\right)}$$

$$I = \left(u_o + u_p\right) \cdot \left(\overline{u_o} + \overline{u_p}\right)$$

$$I = u_o \cdot \overline{u_o} + u_o \cdot \overline{u_p} + u_p \cdot \overline{u_o} + u_p \cdot \overline{u_p}$$

$$I = 2 + u_o \cdot \overline{u_p} + u_p \cdot \overline{u_o}$$

The transmissivity of the film in the linear region:

$$t_A = m \cdot I + b$$

$$t_A = I$$

We'll assume:

Then the reconstructed beam, H is given by:

$$H = u_c \cdot I$$

$$H = u_c \cdot \left(2 + u_o \cdot \overline{u_p} + u_p \cdot \overline{u_o}\right)$$

$$H = 2 \cdot u_c + u_c \cdot u_o \cdot \overline{u_p} + u_c \cdot u_p \cdot \overline{u_o}$$

The term $u_c \cdot u_p \cdot \overline{\left(\left(u_o\right)\right)}$ is called the primary image. The term $u_c \cdot u_o \cdot \overline{\left(\left(u_p\right)\right)}$ is called the conjugate image.

If you want the primary image coming out of the hologram to look just like the original object image, u_p then $u_c \cdot \overline{u_o}$ must equal unity. This will occur if $u_c = u_o$. In other words, to get a perfect image of the real object, the reconstructing beam must be the same (position, color) as the original reference beam. To have a perfect conjugate image, then $u_c \cdot u_o$ must equal unity. This will occur if $u_c = \overline{u_o}$. In other words, the reconstructing reference beam must be the conjugate of the original reference beam.

3. BENEFITS OF 3D VISUALIZATION IN VISUAL DETECTION

It is believed that 3D displays are more compatible with the operator's mental model of a 3D world than is a traditional 2D display and should be used to represent 3D worlds, such as a visual scene of moving vehicles [2]. While 2D representations provide the user with the necessary information to reconstruct a 3D picture, 2D renderings require mental gymnastics to integrate and reconstruct the picture. There have been two basic arguments for implementation of 3D displays: the visual scene of a 3D world is more intuitive and natural representation than 2D displays, and a single integrated object reduces the need for a mental integration of two or three representations [3]. In experiments comparing pilots' initiation of evasive maneuvers to avoid collision, findings show that pilot decision time with 3D displays was 3 to 6 seconds faster than with 2D displays [4]. These researchers contend that these results are attributable to the fact that pilots must assimilate and integrate information from 2D displays into a coherent 3D image or mental model of the environment. In another study, it was found that user performance with 3D stereoscopic displays exceeded performance of those using 2D displays for various tasks like visual search, cursor positioning, and tracking [5]. Stereoscopic displays have also been judged superior for visual search and interactive cursor positioning tasks, for spatial judgment tasks, and for communication of design information [6]. These studies support the hypothesis that potential benefits exist for using 3D displays for tasks similar to those observed in military target detection.

CURRENT SYSTEM CAPABILITIES AND LIMITATIONS

The autostereoscopic holographic imaging display system requires no optical devices to achieve 3-D imaging. The holographic imaging system combines two images from two separate planes observed from two different perspectives into a single image seen through the HOE as one discrete, 3-D object. The human brain integrates the two views into a dramatically high resolution, full color, flicker-free stereo image, which requires no special optical devices. The system is passive, meaning that the image resolution, quality, and interactive speed are entirely dependent on computer processing speed, memory, and technical performance limitations.

Two major problems were observed after developing the prototype HIS system: Moiré effect and chromatic shift. Fig. 1 depicts the moiré effect. In Optics, the moiré effect is the geometrical design that occurs when a aset of straight or curved lines is superimposed onto another set. As shown, the 3-D image appears to have an onion-like character. A probable cause is the limitation in mirror size used to develop the HOE. Future work will focus on alternative approaches to eliminate this negative attribute; one idea is to use overlapping eye-boxes.

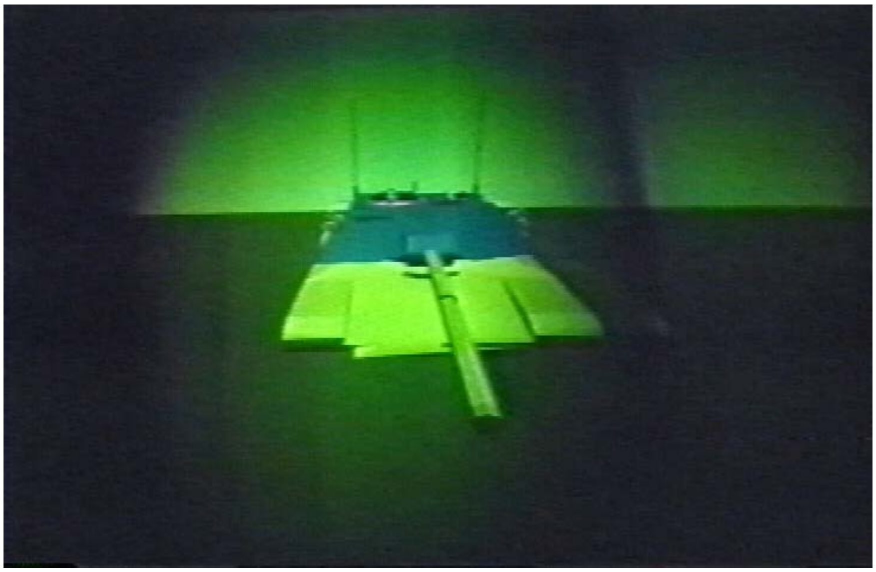

Fig. 1 Moiré Effect

The second problem, chromatic shift, occurred when a user moved his/her perspective up and down while parallel to the HOE, within the limited space of the eyebox. While moving up, the user sees more blues and while moving down, the user sees more reds. The best color is observed when users remain stationary and view the HOE directly perpendicular. Investigation into emulsion processes is required to determine the optimal mixture to eliminate this problem.

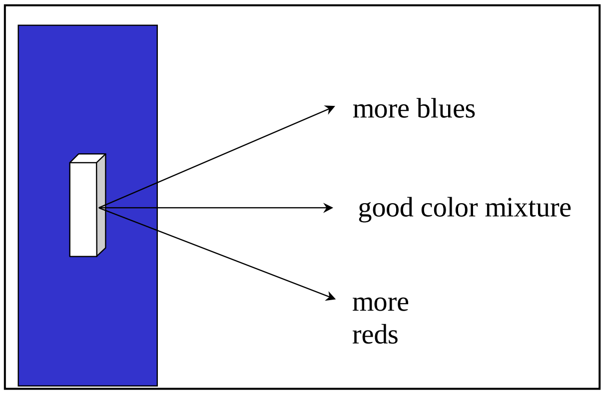

Fig. 2. Chromatic Shift

3. METHOD

3.1 Experiment Design

An experimental design depicted in Fig. 3 was developed to assess performance comparisons between depth perception in conventional 2D and 3D holographic imaging systems. Individual response times, vehicle detection rates, and subjective comments were used to assess and compare the two test configurations.

System Configuration	
2D View	3D View
N=8	N=8

Fig. 3. Depth Perception Experimental Design

3.2 Participants

Twenty test participants were selected from a population within the U.S. Army Tank-automotive and Armaments Command (TACOM) Warren, Michigan. Test participants were randomly assigned to either the 2D or 3D systems configuration. Test participants were pre-screened for visual acuity using a Snellen eye chart and screened for color vision deficiencies using the Ishihara color charts. All participants had at least aided 20/20 visual acuity.

3. 3 Apparatus

The system used in the experiment is shown schematically below in Fig. 4 and a close-up picture of the projectors and reflecting mirror is shown in Fig. 5. With the present system, both computer generated images and recorded video can be displayed. Whether the imagery is computer generated or from a video camera, each of the two projectors displays one constant view from a certain angle. The HOE in this case acts like a transmitting lens and focus' the stereoscopic view at the position of the observer. A holographically designed lens is superior to using something like a large plastic Fresnel lens because the spatial resolution of the Fresnel lens is limited by the height of the ridges, whereas the laser- made HOE is not so limited. The HOE is physically 112 cm (H) by 79 cm (V) in size. The stimuli covered the entire area of the HOE. The vehicles displayed in the test were typically about 12 cm by 10 cm in size. The pixel resolution was that of the SHARP projectors used to display the stimuli, which was 644 (H) by 480 (V). The subjects sat at a distance of 1.6 m from the HOE lens giving an instantaneous field of view (IFOV) of 40 (H) by 29 (V) degrees or 16 pixels/deg. In the future, the current configuration will be expanded to integrate higher resolution and brightness Hughes projectors. Experimentation is planned to evaluate the effects of the increased technical performance obtained when using the Hughes projectors.

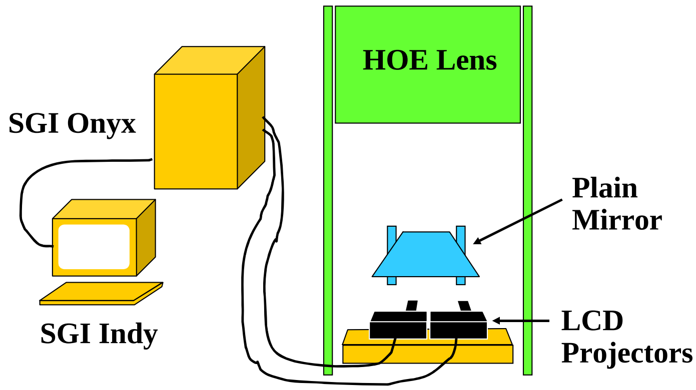

Fig. 4 TARDEC Holographic Imaging system

Fig. 5 Projectors used in the holographic test

4. PROCEDURE

Prior to the experimentation each subject was screened for vision deficiencies, were given a brief introduction that included a general purpose of the experiment, and were instructed on how to respond to the experimental visual stimuli. A 3 minute training video sequence taken from the same data set as the stimuli set were shown to each subject. The experimental task consists of the following: each subject viewed a video sequence of oncoming cars and vans driving on a typical road in Warren, Michigan; subjects were then asked to identify when they visually detected a vehicle turning on its turn signal when making a lane change by depressing the space bar on a lap top computing timing device. Response times were taken and the number of correct detections and misses were computed from observer responses. All measurements were taken in milliseconds. Each subject viewed the identical video sequence through one of the test display conditions, either the 2D conventional system or the 3D holographic imaging system. The only factor varied in this experiment was the dimensionality of the displayed image. The null hypothesis states that there was no difference between 2D and 3D displays when subjects are asked to visually detect turn signals.

5. RESULTS AND DISCUSSION

Study results were mixed, interesting, and somewhat unexpected. The results shown in Fig.'s 6 and 7, are that the use of the 3D HOE increased the number of hits, or correct detections and reduced the number of misses for both vehicles. In other words, using the 3D HOE system increased the perception of accuracy of moving vehicles. The sample size used in this experiment was the minimum required to give a reliability in probability of detection of 0.2 [7,8].

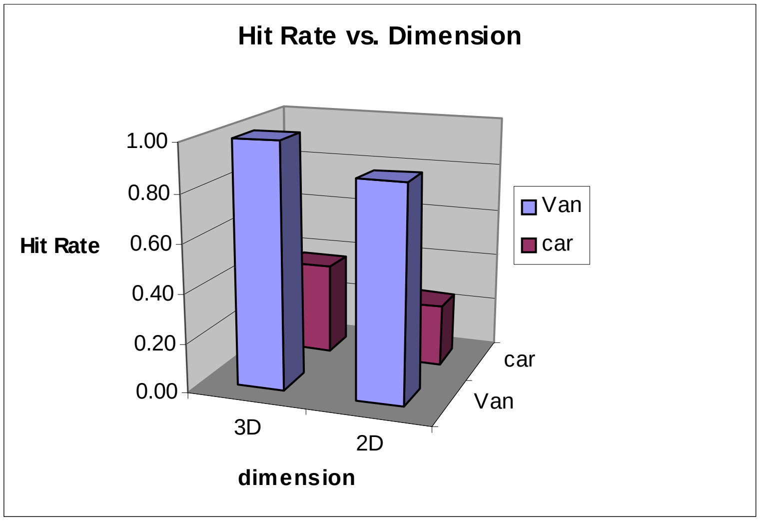

Fig. 6 The holographic system gave a greater detection rate for both vehicles

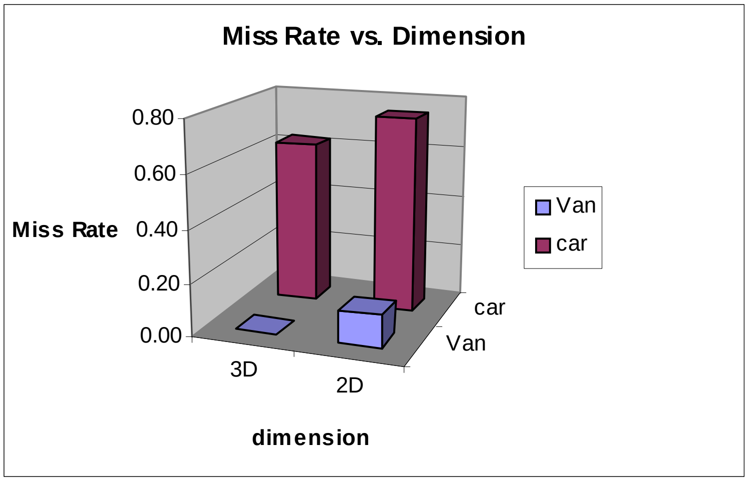

Fig. 7 The holographic system gave a smaller miss rate for both kinds of vehicle.

5.1 SPECTRAL COMPARISONS

A spectraphotometric camera was used to measure the spectrum of light from the HOE for a MacBeth Chart as a source. The MacBeth chart is used routinely by the photographic community to calibrate cameras and color copiers. CIE coordinates were measured for the chart's many colors in the field under natural illumination, in the laboratory through a Hughes Projector, and then displayed through SHARP LCD projectors and the HOE. These plots are shown below. The size of the MacBeth chart was kept small so as to minimize any distortion that might occur because of lens imperfections.

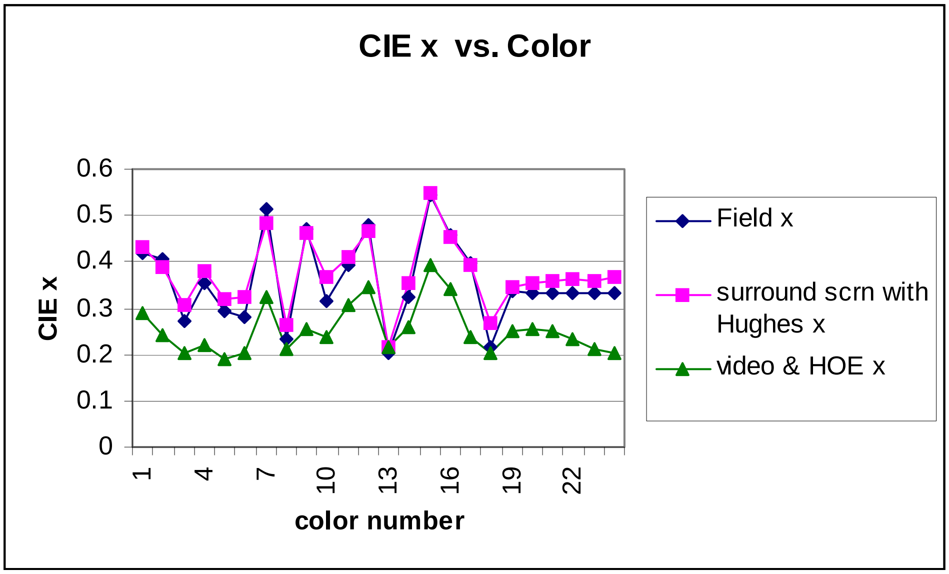

Fig. 8

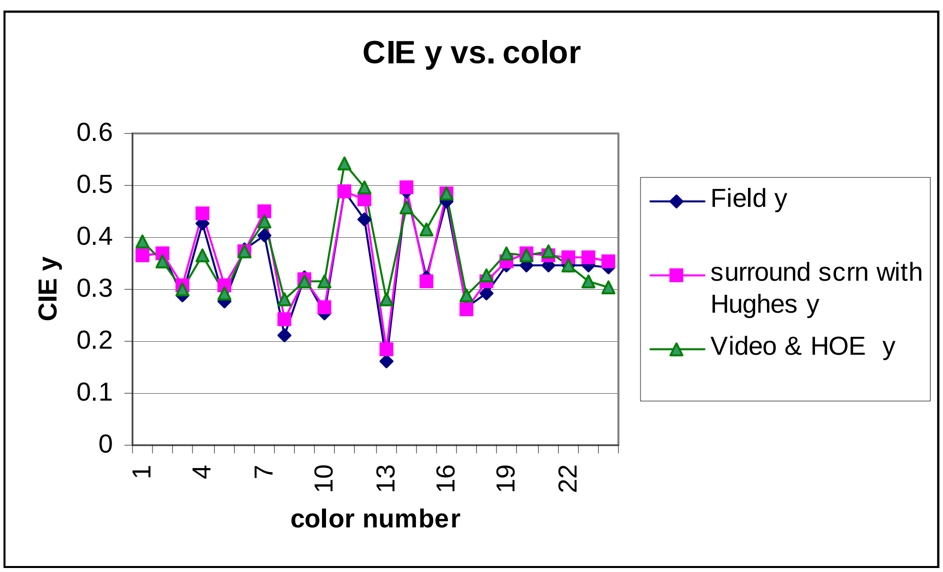

Fig. 9

A correlation of 0.85 to 0.95 was achieved for these systems between field spectral values and laboratory values. So despite any visual distortion due to imperfections in the HOE lens, the chromatic purity of the stimuli is not that much different than other projection sources.

Fig.s 10 through 13 show the spectral changes the HOE introduces into an image projected by a LCD projector. In each figure, the spectral readings were taken with and without the HOE. CIE x,y, and Y parameters are shown. Generally, there is a correlation of 0.9 between the spectral values recorded off a 2D image with those recorded through the HOE.

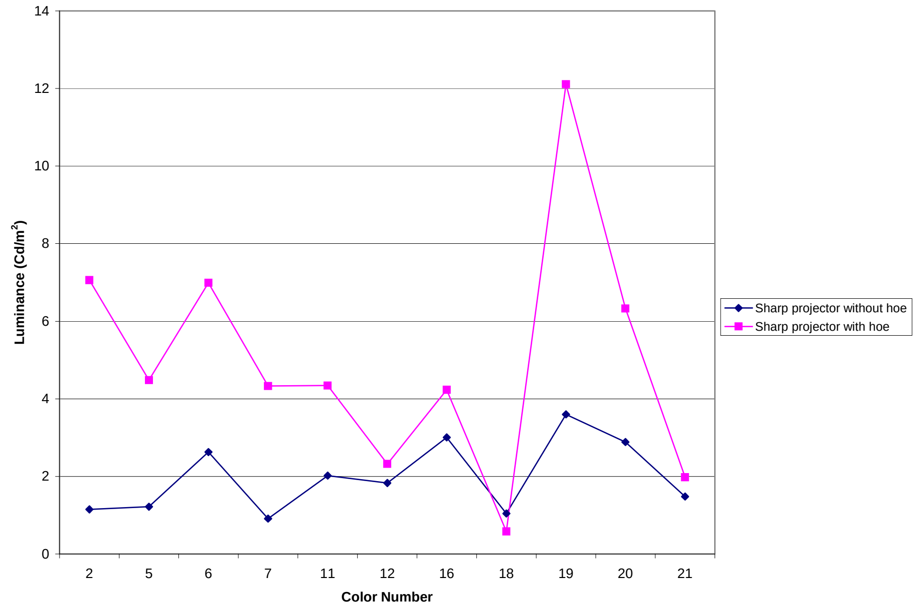

Fig. 10

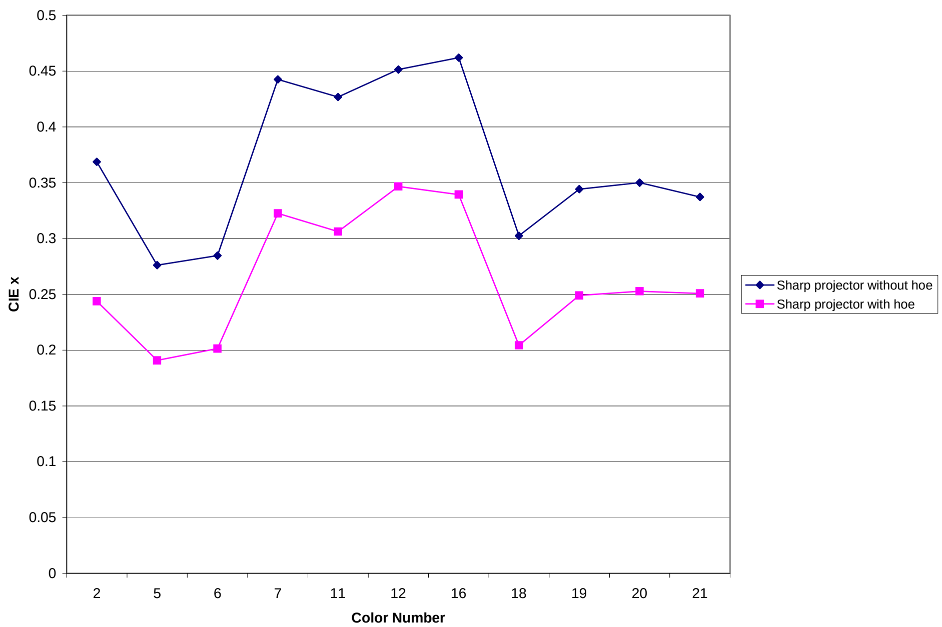

Fig. 11

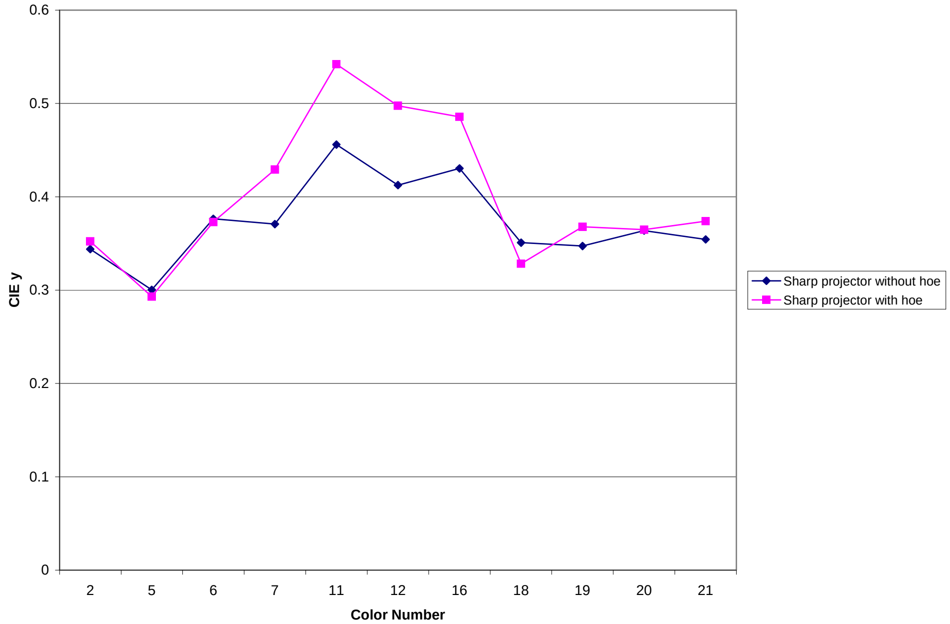
0.6
0.5
0.4
0.3
0.2
0.1
0
CIE y
2
5
6
7
11
12
16
18
19
20
21
Color Number
Sharp projector without hoe
Sharp projector with hoe

Fig. 12

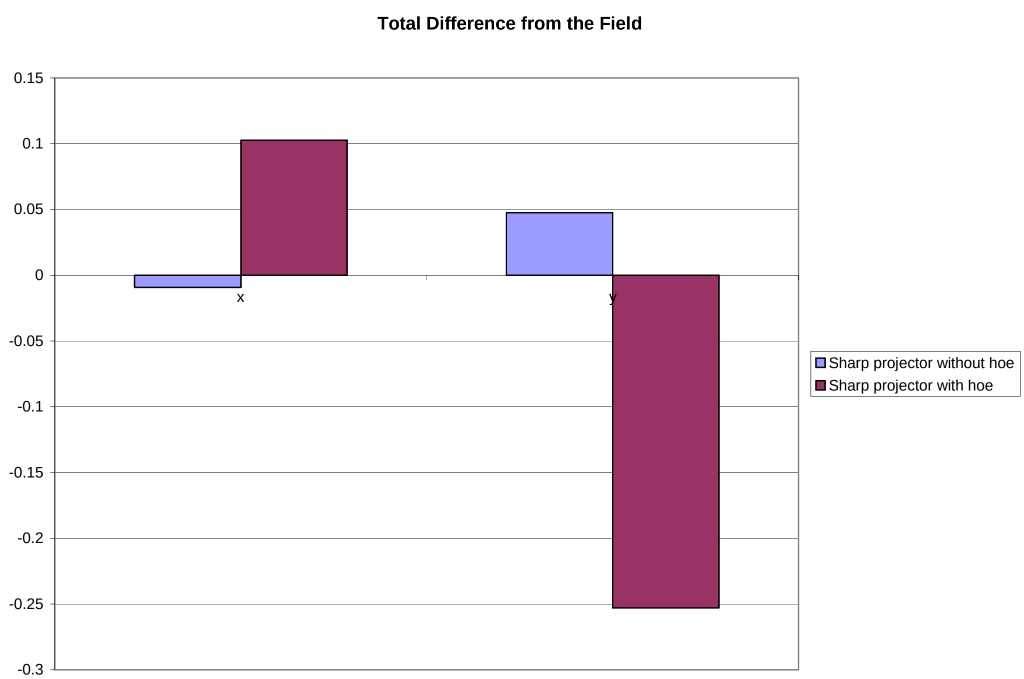
Total Difference from the Field
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
-0.3
x
y
Sharp projector without hoe
Sharp projector with hoe

Fig. 13

6 CONCLUSIONS

Application of 3D displays into military developmental systems has been approaching a reality at a very fast pace. The results of this study indicate that the addition of 3D to displayed visual information will be a benefit to training simulations and the perception of embedded targets in scenes. Additional directed research is needed since a strong emphasis on computer display systems in commercial and industrial computer graphics applications is expected in the future. It has been projected that the real-time simulation will grow 46% by the year 2000 [9]. In light of these projections, additional insights are needed to gain a better understanding of how to apply 3D display technologies to training simulations while maintaining and improving performance of the users and more specifically for military target detection.

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